Postharvest Innovations for Food Security in Nigeria: Integrating Storage, Preservation, and Processing Technologies

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ARTICLE HISTORY
Received Date: 6th June, 2025
Accepted Date: 31st July, 2025

http: www.njphr.nspri.gov.ng
ISSN: 2630-7022

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CONFLICT OF INTEREST: None
ETHICAL APPROVAL: Not Applicable

This is a publication of the Nigerian Stored Products Research Institute (NSPRI)

OPEN ACCESS

Abstract

Postharvest losses remain a critical challenge in Nigeria, affecting food security, economic development, and rural livelihoods. This study employs a qualitative systematic review methodology, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure transparency and rigour. The review aims to examine technological innovations *in postharvest storage, preservation, and processing relevant to Nigeria; analyse the roles of Agricultural Extension, Rural Sociology, and Biosystems Engineering in facilitating adoption and sustainability; evaluate the economic, socio-cultural, and institutional factors* influencing *postharvest innovation outcomes. A comprehensive literature search was conducted across scholarly databases and relevant institutional publications to draw insights from 35 sources with triangulation of peer-reviewed and grey literature published between 2015 and 2025 that investigated postharvest innovations in Nigeria. A thematic analysis identified four key categories: adoption through agricultural extension platforms, technological adaptation of postharvest tools, socio-cultural factors including gender disparities and trust networks, and institutional synergies and policy coherence. While innovations have improved shelf life and farmer incomes, challenges persist: poor rural infrastructure, gender disparities, fragmented extension services, and inconsistent policy support. Trust-building and community engagement were noted as critical to fostering technology uptake. The study recommends targeted investments in decentralised infrastructure, promotion of gender-inclusive innovation models, and coordinated public–private partnerships to accelerate impact. In Nigeria, a revitalised extension system and coherent policy framework are essential to embed postharvest technologies into food systems. These measures will help transform the sector into a resilient and equitable pillar for national food security.*

Keywords:
Agricultural innovation, Food security, Gender inclusion, Postharvest technologies, Rural

Introduction

In Nigeria, postharvest losses remain a critical barrier to achieving food security, with implications for agricultural productivity, income generation, rural livelihoods, and national economic stability. These losses result in reduced food availability, increased prices, and diminished farmer income. They also exacerbate poverty and malnutrition, particularly in rural communities reliant on agriculture. To underscore this review's urgency and contextual relevance, the Food and Agriculture Organization (FAO, 2020) reports that over 40% of food produced in sub-Saharan Africa goes to waste after harvest because of poor preservation practices, inadequate storage systems, and insufficient processing infrastructure. In Nigeria specifically, postharvest losses are estimated to range between 20–40%, depending on crop type and region, affecting staples such as maize, tomatoes, and yams (Bolarin & Bosa, 2015), thereby negatively impacting smallholder farmer welfare and rural economies.

These challenges are heightened by increasing urbanisation, a rapidly growing population, and mounting pressures on food demand. Postharvest losses must be drastically minimised to achieve consistent food availability, improve nutritional outcomes, reduce dependence on imported food, and enhance competitiveness in

How to cite:
Makinde, O. O., & Akinmolafe, A. O. (2025). Postharvest Innovations for Food Security in Nigeria: Integrating Storage, Preservation, and Processing Technologies. *Nigerian Journal of Post-Harvest Research*, 3(2), 45-56.

domestic agriculture (Olayemi et al., 2019; Yusuf & Okoruwa, 2021).

Globally, postharvest innovation has been identified as a strategic pathway for sustainable agricultural sector transformation. Mobile processing units, solar-powered drying, off-grid refrigeration, and hermetic storage have shown promise in reducing losses in agrarian products (Affognon et al., 2015; Kitinoja, 2019). In sub-Saharan Africa, zero-energy cool chambers and Purdue Improved Crop Storage (PICS) bags have significantly extended shelf life and reduced perishable spoilage (Musa et al., 2020). For instance, field trials by the Nigerian Stored Products Research Institute (NSPRI) in Benue and Plateau States showed that ZECCs extended the shelf life of tomatoes and peppers by 3–5 days, providing a low-cost alternative for off-grid communities. Similarly, in Kano State, adopting PICS bags among cowpea farmers led to an 80% reduction in insect-related storage losses, eliminating the need for chemical preservatives and aligning with rural safety standards (Baributsa et al., 2017). Nonetheless, effective adoption and scalability of these innovations require interdisciplinary approaches tailored to farmers' socio-economic realities and preferences (Adetunji et al., 2020).

This review integrates the intersection of three critical fields, Agricultural Extension, Rural Sociology, and Biosystems Engineering, in advancing postharvest transformation within Nigeria's socio-technical framework. Agricultural Extension is central in disseminating knowledge, building capacity, and connecting farmers to markets and support services. Rural Sociology offers insights into the social, institutional, and cultural factors influencing technology adoption, including community norms, gender roles, and collective action. Biosystems Engineering provides the technical basis for designing, adapting, and refining postharvest technologies.

This review aims to synthesise evidence from scientific publications between 2015 and 2025 to investigate how storage, preservation, and processing technologies can reduce postharvest losses and bolster food security in Nigeria. It comprehensively examines the innovations, barriers, and prospects defining Nigeria's postharvest landscape. Specifically, this review aims to: examine technological innovations between 2015 and 2025 in postharvest storage, preservation, and processing relevant to Nigeria; analyse the roles of Agricultural Extension, Rural Sociology, and Biosystems Engineering in facilitating adoption and sustainability; evaluate the economic, socio-cultural, and institutional factors influencing postharvest innovation outcomes; and propose a conceptual model for integrating interdisciplinary postharvest innovation systems in Nigeria. This enhances food security, mitigates food loss, and promotes inclusive rural development through evidence-based strategies.

Methodology

This study employed a qualitative structured recapitulation, drawing from scholarly secondary data sources to assess postharvest innovations in Nigeria. The review process adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 specifications, ensuring imitability, sheerness and methodological stringency (Page et al., 2021). This approach was appropriate for harmonising interdisciplinary insights across Biosystems Engineering, Rural Sociology, and Agricultural Extension within the Nigerian context.

An exhaustive exploration covered major academic databases, including Web of Science, Scopus, Google Scholar, and ScienceDirect. Indexes were trimmed to guarantee overarching reportage, including combining terms like "food systems and agricultural extension", "postharvest storage", "postharvest processing innovations", "rural sociology and postharvest", "food preservation technologies Africa", and "food security and biosystems engineering". Search terms were intentionally tailored to the Nigerian agricultural landscape, and database filters were adjusted to prioritise Nigeria-specific content. Technical reports and institutional publications from organisations like the Nigerian Stored Products Research Institute (NSPRI), the Food and Agriculture Organization (FAO) and the International Institute of Tropical Agriculture (IITA) were also reviewed. Documents from national bodies such as the Federal Ministry of Agriculture and Rural Development (FMARD) and FAO's Nigeria-focused publications were included for added contextual specificity.

This study adhered to a strict inclusion benchmark to ensure academic rigour and thematic relevance, selecting only peer-reviewed journal articles published between 2015 and 2025. The central focus remained on research grounded in the Nigerian context and contributions that intersected with at least one of the following disciplines: Rural Sociology, Agricultural Extension, or Biosystems Engineering. Complementary sources such as technical reports, case studies, meta-analyses, and review articles were included where they provided Nigeria-specific empirical or conceptual insights into postharvest

innovation. While certain sub-Saharan Africa (SSA) literature was referenced in the introduction and discussion sections to enrich contextual understanding of postharvest losses, these sources were not part of the systematic review or synthesis. Their inclusion was intended to frame Nigeria's challenges within a broader regional landscape. However, articles focused only on primary production, preharvest, or unrelated agricultural themes, literature published over a decade, and studies without contextual, empirical or theoretical relevance to Nigeria or the postharvest field were excluded from the review. Publications older than 2015 or lacking Nigeria-specific framing were systematically omitted to ensure thematic consistency. A structured data extraction template was used to collect details from the selected studies, including authorship, publication year, geographic focus, crop or commodity of interest, type of innovation, methodological approach, disciplinary framing, and key findings. Thematic synthesis was conducted using the method outlined by Thomas and Harden (2008), facilitating the identification of recurrent patterns and higher-order themes. Thematic synthesis enabled the identification of recurrent narratives and analytical clusters tailored to Nigeria's postharvest landscape. Four thematic clusters emerged: (i) Technological Innovations in Postharvest Systems, including hermetic storage, solar drying, and bio-based packaging technologies; (ii) Adoption and Diffusion through Agricultural Extension which involves examining knowledge transfer pathways, farmer training, and the role of community-based facilitators; (iii) Socio-Cultural and Gender Considerations, focusing on access disparities, traditional beliefs, and the influence of household role; (iv) Institutional and Infrastructural Enablers, encompassing policy frameworks, public–private partnerships, and the role of research institutions. These clusters reflect the multi-dimensional nature of postharvest innovation and sustainability in Nigeria.

Triangulation was employed to enhance the trustworthiness of the synthesis by incorporating diverse data sources, including peer-reviewed studies, technical reports, and institutional publications. Although member checking was not feasible due to the reliance on secondary data, credibility was ensured through meticulous adherence to the PRISMA guidelines and transparency in the selection and analysis of literature. The initial search yielded 112 studies. After the removal of duplicates and irrelevant titles, 73 studies remained. The screening process was first of abstracts, then full texts, conducted independently by two reviewers to guarantee fairness. Debates were discussed through discretion. Final consensus was reached through critical discussion. Eventually, 35 studies met all inclusion criteria and were included in the synthesis.

Results and Discussion

Adoption and diffusion through agricultural extension

Agricultural extension services are vital in bridging the divide between technological innovation and practical application. In Nigeria, where postharvest losses affect both productivity and rural incomes, the effectiveness of modern storage and preservation solutions often depends on how well they are communicated and adopted across farming communities. Extension-driven knowledge transfer has become central to this adoption pathway through structured training, community engagement, and feedback loops.

Programs such as farmer field schools, mobile alerts, radio dissemination, and NGO-led sensitisation campaigns have enabled broader uptake of postharvest innovations (Affognon et al., 2015). Hermetic storage solutions, including PICS bags and metal silos, as well as ZECCs and solar-powered cold hubs, have been demonstrated through these platforms, allowing farmers to observe functionality and make informed decisions. Extension officers have proven instrumental in contextualising these technologies to local farming systems, boosting farmer confidence and relevance. Nevertheless, agricultural extension systems still face substantial limitations. Challenges such as underfunding, staff shortages, and inadequate field reach persist, particularly in remote and underserved zones (Ogunniyi & Ajao, 2019). This institutional fragility undermines consistent training delivery and follow-up, essential for long-term adoption and adaptation. Strengthening these services through increased funding, localised training modules, and participatory extension models can significantly enhance postharvest innovation diffusion.

Solar drying technologies present compelling examples of where community-based facilitators have supported adoption. Low-cost solar tunnel dryers have been introduced in southwestern Nigeria, particularly among female processors, yielding impressive gains in income and reductions in food spoilage (Eze et al., 2020). In Benue and Oyo states, solar drying led to a 40% increase in revenue and a 60% drop in spoilage among tomato and pepper processors. These figures underscore the impact of technical demonstration and highlight the gender-sensitive design and inclusive

outreach embedded in successful extension initiatives. Similarly, Fashanu et al. (2023) demonstrate that NSPRI-designed solar dryers outperform traditional sun-drying in nutritional retention and microbial safety, reinforcing the value of engineering-supported extension frameworks. Likewise, cassava flash dryer trials conducted in Kwara and Ogun revealed improved consistency in moisture control and reduced labour stress, especially among women processors (Akomolafe et al., 2022).

Despite the potential, many rural communities still lack the technical skills to maintain preservation equipment. Broken parts, poor material quality, and lack of access to spares often disrupt usage (Abdul et al., 2022). Agricultural extension agents are essential in providing hands-on repair training and maintenance education. Localised training hubs and refresher clinics can help sustain equipment longevity and utilisation. Rural preservation strategies, such as bio-preservatives and Modified Atmosphere Packaging (MAP), require specialised handling and awareness. Extension platforms have helped introduce neem-based coatings, aloe vera gels, and starch-derived protective films to small processors. Farmers are increasingly exploring these alternatives through demonstration plots and cooperative trials, particularly where synthetic preservatives are unavailable or unaffordable. For instance, Omotoso et al. (2022) confirm that moringa and neem-based coatings extended shelf life by up to five days compared to untreated produce, especially under humid conditions.

The role of extension services also proved pivotal in Rivers State, where solar-powered cooling systems and ice block units were introduced for fish preservation. With limited access to grid electricity, these innovations helped reduce spoilage rates by over 50% (Abah et al., 2025). Extension officers facilitated training workshops, promoting adoption, routine servicing, and proper usage. The outcome reflects how technical innovation requires guided implementation to achieve measurable postharvest impact. Effective diffusion also benefits from policy synergy. Initiatives that subsidise equipment, integrate postharvest curricula in farmer training, and promote gender equity in extension outreach strengthen uptake across scales. Partnerships involving NSPRI, FMARD, and community cooperatives demonstrate how collaborative frameworks can scale preservation technologies effectively. In sum, agricultural extension remains the linchpin of Nigeria's postharvest transformation. By linking technologies to communities through education, inclusion, and practical support, extension services ensure that innovations exist and thrive. Their role in connecting scientific development with rural realities is strategic and irreplaceable.

Socio-cultural and gender considerations

Socio-cultural dynamics and gender roles influence the adoption and utilisation of postharvest technologies in Nigeria. Across rural communities, entrenched norms often dictate access to resources, decision-making authority, and labour roles, shaping who benefits from innovations and who remains excluded.

Access disparities are particularly pronounced among women farmers and processors, who constitute the bulk of postharvest labour yet face restricted control over income, land, and inputs. Ede & Bakare (2022) reveal that only 18% of female agro-processors in southwestern Nigeria had access to formal extension services, compared to 54% of their male counterparts. Despite their central role in storage, drying, and processing, women often lack the autonomy to invest in preservation technologies without approval from male household heads. This gender gap persists despite policies that mainstream women's participation in agricultural interventions (Auta et al., 2021).

Traditional beliefs also shape technology perceptions and adoption. Local myths about "cold spirits" in mechanical coolers or fears of fermentation affecting crop sanctity hinder acceptance in some communities. Solar drying devices have been misconstrued as instruments that leach 'ancestral strength' from yam tubers in some Delta State villages, indicating the need for culturally sensitive outreach strategies (Chukwudi & Okoro, 2020). Extension personnel have countered these narratives through participatory workshops and inclusion of traditional leaders in demonstration activities, enhancing trust and promoting gradual behavioural change. Household roles and intra-family labour divisions further influence uptake. While women bear the brunt of postharvest tasks, particularly in the drying and packaging of cassava, maize, and vegetables, they are often excluded from the technical training or capital support schemes targeted at 'farmers,' who are assumed to be male. Onuoha et al. (2023) showed that 62% of women engaged in postharvest work were unaware of existing preservation subsidies due to their exclusion from cooperative platforms and decision-making forums.

Yet, when empowered, female processors demonstrate strong innovation uptake. Gender-inclusive projects like the FMARD tomato preservation initiative in Kano have shown that spoilage rates drop and

household incomes rise when women gain access to solar dryers and receive hands-on training. Nwafor et al. (2024) found that women-led drying cooperatives achieved a 55% reduction in postharvest loss within two growing seasons.

Cultural sensitivity and gender responsiveness have thus become essential features of successful technology dissemination. Organisations like NSPRI now prioritise female-headed households and design training materials in local languages to overcome literacy barriers and social exclusion (Abdul et al., 2022). Community feedback loops, female extension facilitators, and inclusive policy design are reshaping access frameworks to ensure equitable and effective postharvest innovations.

Technological innovations in postharvest systems

Many innovative storage technologies have been recommended to address food loss in Nigeria to keep up postharvest standards and better food preservation. Technologies such as metal silos, hermetic storage bags, off-grid solar-powered cold storage, and zero energy cool chambers (ZECCs) have displayed effectiveness in downsizing losses, particularly for staple crops such as legumes, grains, dairy, tomatoes, and fish (Adekola et al., 2020).

Hermetic storage solutions, including Super Grain bags and Purdue Improved Crop Storage (PICS) bags, establish a hermetic ecosystem that stops fungal and pest expansion without chemical preservatives. These innovations have proven serviceable in upholding grain wholeness, particularly in areas predisposed to humidity-related spoilage and pest infestations (Affognon et al., 2015). Nevertheless, acceptance remains unequal due to limited farmer awareness and affordability concerns. While PICS bags are widely promoted in Northern Nigeria, their acceptance in Southern Nigeria remains low due to viable distribution networks and deficient extension services (Ogunniyi & Ajao, 2019). Similarly, metal silos offer permanent, protective storage for maize and other grains, defending against microbial contamination and rodent infestations. Ogunniyi & Ajao (2019) stated that in Kaduna and Katsina states, the distribution of metal silos under the Agricultural Transformation Agenda Programs (ATAP) led to a 30%–50% reduction in maize postharvest losses, illuminating the ability of organised storage interventions in improving food security and farmer resilience.

Beyond dry storage solutions, ZECCs provide a simple yet effective cooling mechanism for preserving perishables without electricity. Using evaporative cooling principles, these chambers help farmers extend the shelf life of fruits, vegetables, and dairy products, making them particularly valuable in regions with unreliable power supply (Musa et al., 2023). As Nigeria continues to experience energy deficits that disrupt refrigeration systems, off-grid solar-powered cold storage has emerged as a viable alternative. Initiatives such as community cold hubs and modular solar coolers are helping farmers and traders maintain the quality of perishable goods. These systems are especially beneficial in preserving tomatoes, fish, and leafy greens, key commodities highly susceptible to rapid deterioration in Nigeria's warm climate (Musa et al., 2023). However, implementing these solutions at scale requires sustained investment, technical expertise, and policy support to ensure long-term viability.

The Nigerian Stored Products Research Institute (NSPRI), has played a pivotal role in piloting, adapting, and scaling many of these technologies. NSPRI's development of hermetic steel silos, evaporative cooling systems, and community outreach demonstrations has proven instrumental in extending shelf life and reducing postharvest losses across rural Nigeria. Its research contributions and field-based interventions lend institutional weight to Nigeria's postharvest transformation agenda.

Despite the effectiveness of these technologies, their adoption remains constrained by several key challenges. One of the most pressing issues is affordability. Many smallholder farmers struggle with the high initial cost of storage innovations, making it challenging to transition from traditional storage methods to modern solutions (Adekola et al., 2020). Financial assistance programs and subsidies could help bridge this gap, making these technologies more accessible to vulnerable farming populations. Another major obstacle is the lack of widespread awareness and education on postharvest management. Many farmers, particularly those in remote rural areas, are either unaware of these technologies or lack the training to use them effectively (Ogunniyi & Ajao, 2019). This underscores the need for stronger agricultural extension services to facilitate knowledge transfer and encourage adoption.

In addition to education and affordability concerns, market access and distribution infrastructure pose significant hurdles. Many of Nigeria's agricultural regions suffer from poor road networks and inefficient transportation systems, making it difficult for farmers to access markets and storage facilities on time (Musa et al., 2023). Investment in rural infrastructure,

including better roads, storage hubs, and logistics networks, is crucial to reducing postharvest losses and ensuring farmers can sell their produce efficiently (Adekola et al., 2020). Additionally, government policies should support the development of aggregation systems that allow farmers to pool resources and collectively invest in storage solutions that might otherwise be unaffordable for individual producers (Ogunniyi & Ajao, 2019). Furthermore, the environmental benefits of improved storage technologies cannot be overlooked. Diverting agricultural residues and reducing food spoilage directly contribute to climate change mitigation by lowering methane and carbon dioxide emissions associated with decaying produce and open-field burning (Musa et al., 2023). Additionally, livestock manure from animals fed with agroresidues can be reintegrated into the soil, promoting regenerative agricultural practices that improve fertility and sustainability (Birthe et al., 2023). Circular economy models that emphasise resource efficiency in food production offer a path toward achieving national climate goals while enhancing rural livelihoods (Affognon et al., 2015).

Policy intervention is essential in scaling up postharvest storage technologies. Governments and research institutions must collaborate to create an enabling environment for adopting agrostorage innovations. Financial incentives such as subsidies, grants, and microcredit facilities can help smallholder farmers afford storage solutions that significantly reduce waste (Adekunle & Oseni, 2020). Public-private partnerships can enhance technology dissemination, ensuring that innovative storage systems reach small-scale farmers across diverse agroecological regions (Musa et al., 2023). Nigeria's policy framework must also address gender disparities in technology adoption, as women farmers often face additional barriers in accessing financial resources and agricultural inputs (Ogunniyi & Ajao, 2019).

Policy and institutional synergies

The diffusion of postharvest technologies in Nigeria is not merely a matter of innovation availability; it is deeply contingent on policy frameworks, institutional coordination, and the strength of multi-level partnerships. While extension services and technological demonstrations are central, their efficacy relies heavily on the enabling environment created by public and private sector synergy.

At the federal level, Nigeria's policy landscape has evolved to support postharvest transformation. The adoption of the National Agricultural Extension Policy (NAEP) in 2023 by the Federal Ministry of Agriculture and Food Security (FMAFS) marked a turning point, emphasising pluralistic service delivery, ICT integration, and gender-sensitive programming (Federal Ministry of Agriculture & Food Security, 2023). This policy recognises the need for customised extension models, especially for underserved regions and processors. Institutes such as the Nigerian Stored Products Research Institute (NSPRI) have led in aligning research output with community-level needs. Through its Research Outreach Department, NSPRI has developed technologies like solar dryers, evaporative cooling chambers, and hermetic containers with scale-up strategies that involve direct training, user feedback mechanisms, and post-installation monitoring (Abdul et al., 2022). These efforts have reinforced the shift from pilot innovations to system-wide adoption across Nigeria's six geopolitical zones.

Collaborations with NGOs and cooperative societies have also facilitated technology access and adaptation. In Ogun and Nasarawa states, joint efforts between NSPRI and female-led cooperatives have led to the distribution of over 800 low-cost preservation kits, accompanied by on-site training sessions delivered in local dialects (Akomolafe et al., 2022). These community partnerships help ensure that end users introduce, own, and sustain technologies. Subsidy programs for preservation equipment have emerged as game-changers, particularly for resource-poor farmers. Under the FMARD Solar Preservation Subsidy Scheme (SPSS), over 500 rural women in tomato clusters received solar tunnel dryers at 60% subsidised rates, reducing spoilage and enhancing bargaining power in local markets (Nwafor et al., 2024). However, gaps in implementation persist, especially where eligibility criteria or political considerations hinder equitable distribution.

Local government councils and agricultural development programs (ADPs) often link national policy and grassroots impact. Yet, many ADPs suffer from fragmented mandates, poor inter-agency coordination, and limited budgetary autonomy, which can derail the flow of postharvest support services (Ogunniyi & Ajao, 2019). Integrated planning frameworks, where LGAs align with NSPRI, FMARD, and donor agencies, can help harmonise outreach strategies and improve accountability. Additionally, policy instruments targeting youth and women have shown promise. Programs like AgroHubs for Youth Employment and the Women-in-Processing Initiative (WiPI) have bundled training, equipment access, and

market linkages, addressing adoption and long-term sustainability. These models exemplify how institutions can move from provision to empowerment. Despite the strides, policy silos and bureaucratic inertia still pose significant obstacles. Streamlining regulatory protocols for technology approval, decentralising training centres, and increasing budgetary allocations for postharvest innovation must become urgent priorities. When institutions co-create with communities and policies reflect local realities, the pathway from invention to livelihood transformation becomes smoother.

Case studies

Case 1: Tomato Jos project, Kaduna

The Tomato Jos Project in Kaduna has shown how well integrated postharvest solutions work to lower losses and raise farmer profits. Within two years, the program has decreased postharvest losses for 250 farmers by 60% by combining cold storage, solar dryers, and farmer cooperatives (USAID, 2020). The project's success is ascribed to its interdisciplinary approach, in which sociologists assisted in developing cooperatives and opening markets, engineers created drying and storage technology, and extension agents instructed farmers on best practices (Tomato Jos, 2024).

Case 2: Cassava flash dryers, Ogun State

By promoting flash dryers for cassava processing in Ogun State, the Federal Ministry of Agriculture and Food Security (FMAFS) and the International Institute of Tropical Agriculture (IITA) have significantly increased the shelf life of Gari, decreased drudgery, and raised market prices (IITA, 2021). In places where rural sociologists worked with farmers early on to ensure that the technology was economically feasible and culturally acceptable, adoption rates were greater (Afolabi et al., 2021). By showing that engineering solutions are inadequate without social integration, the program emphasises the significance of community engagement in technology distribution (IITA, 2021).

Case 3: Off-grid refrigeration for fish in rivers state

Inadequate refrigeration facilities have caused significant spoilage rates for Rivers State's fishermen. Fish preservation without dependency on grid electricity was made possible by engineering solutions that supplied ice blocks and solar-powered coolers (NIFOR, 2022). Agricultural extension agents were essential in teaching fishermen how to use and maintain the intervention to guarantee its long-term viability. Under their direction, spoiling rates were reduced by more than 50%, improving local communities' food security and financial stability. Effective extension services have been crucial in encouraging the adoption and upkeep of food preservation methods, hence improving rural populations' living standards (Abah et al., 2025).

Case 4: Rice innovation platform in ebonyi

A prime example of multi-stakeholder cooperation is the Rice Innovation Platform in Ebonyi, which brings together engineers, extension agents, and community leaders to promote upgraded rice mills and threshers (Onyema et al., 2023). The platform has improved processing efficiency, raised earnings, and fortified local rice markets by combining technical know-how with farmer training and socio-economic research (AfricaRice, 2024). This shows that technological adoption is most successful when accompanied by education and community participation, thus emphasising the value of interdisciplinary approaches in scaling agricultural innovations (Ezeh et al., 2022). Biosystems Engineering, Agricultural Extension, and Rural Sociology must be integrated for postharvest innovations to be implemented successfully. Case studies from Kaduna, Ebonyi, Rivers and Ogun show how technical solutions, farmer education, and socio-economic factors combine to improve rural livelihoods, decrease losses, and increase food security. In the future, interdisciplinary cooperation should be prioritised in policy frameworks to guarantee that technology developments are affordable, culturally appropriate, and sustainable.

Conceptual framework: the innovation systems approach

The Innovation Systems Approach positions postharvest technology adoption as a collaborative, non-linear process shaped by actors such as farmers, researchers, extension agents, processors, and policy institutions, all operating within enabling environments (Bello & Yakubu, 2023). As presented in Figure 1, knowledge flow from research to practice depends on tailored dissemination pathways. Institutions like the Nigerian Stored Products Research Institute (NSPRI) have demonstrated that field-level demonstrations and community-centred trainings are vital for contextualising innovations (Adegbola & Ajayi, 2022; Obianefo et al., 2025). Social capital and trust networks play a critical role. Farmer cooperatives, religious associations, and peer groups often serve as informal channels for evaluating and validating new technologies. This form of collective confidence

fosters quicker and more sustained adoption (Akpan-Etuk, 2024).

Feedback loops between innovators and users enable continuous refinement. Technologies such as solar dryers and hermetic drums have benefited from direct feedback mechanisms mediated by extension officers and cooperative leaders, making them more user-friendly and efficient (Adegbola & Ajayi, 2024). Institutional arrangements such as cross-agency coordination and coherent regulatory frameworks determine diffusion speed and scale. Successful scaling has occurred where institutions like FMARD, NSPRI, and donor organisations have aligned objectives and implementation strategies (Ozor et al., 2025; Nigerian Stored Products Research Institute, 2025).

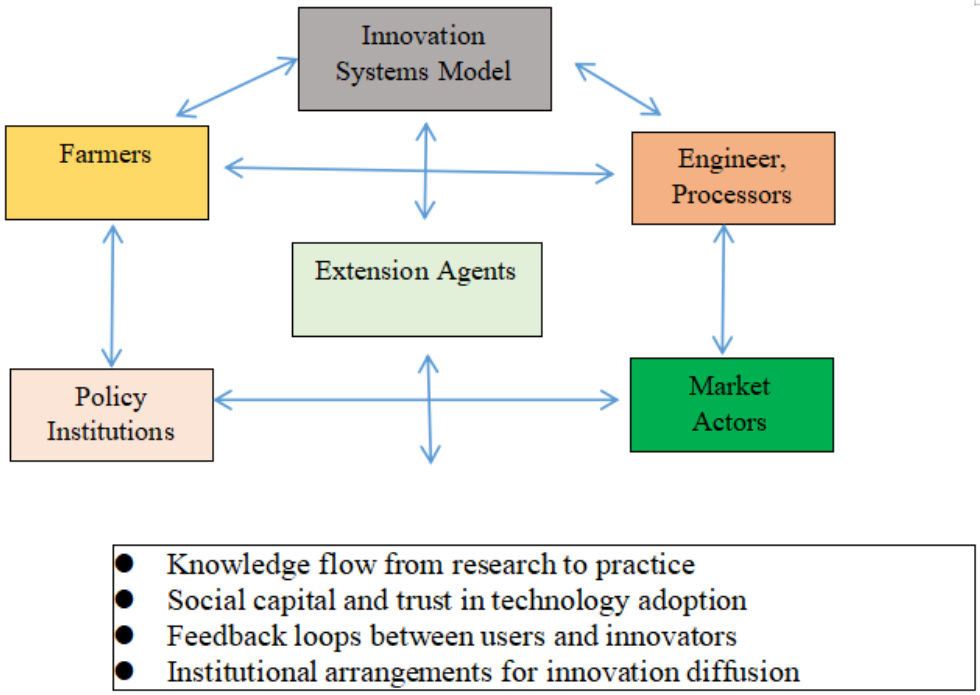

Figure 1. Conceptual Innovation System Model for Nigerian Postharvest Systems

Emerging challenges in Nigeria's postharvest systems

The postharvest industry in Nigeria nevertheless faces enduring obstacles that prevent widespread adoption and impact food security, despite notable developments in processing, storage, and preservation technology. Several issues, such as disjointed extension services, gender inequality, infrastructural deficiencies, and lax enforcement of policies, cause high postharvest losses and economic inefficiencies. A multifaceted strategy incorporating inclusive innovation tactics, interdisciplinary cooperation, and policy reforms is needed to address these problems. Inadequate policy enforcement is one of the most significant issues facing Nigeria's postharvest industry. Although several regulations are in place to aid in agricultural development, their application varies, resulting in ineffective market regulation and technology uptake.

Nearly 70% of Nigeria's agricultural output is exported as raw materials, and studies show that 40–45% of agricultural produce is lost after harvest, exacerbating food insecurity and economic instability (Adebayo & Adekunle, 2022). Strengthening public-private partnerships for rural infrastructure and research and development (R&D) is essential to addressing this. The creation of economical processing, preservation, and storage technologies can be aided by cooperation between agribusinesses, government organisations, and academic institutions (AgroNigeria, 2024). Policy frameworks should also prioritise enforcement measures to guarantee that postharvest innovations are available, flexible, and sustainable (Balogun et al., 2021).

In Nigeria's agricultural sector, women are also essential, especially in small-scale processing and preservation operations. Gender differences in access to financial resources, training opportunities, and mechanised instruments still constrain their involvement in postharvest innovation. According to research, women farmers and processors frequently encounter obstacles when trying to obtain extension

assistance, market connections, and loans, which limit their capacity to expand their businesses and enhance their standard of living (Nwachukwu et al., 2021). For fair adoption of technology, gender inclusive innovation initiatives must be put into practice. Women's involvement in postharvest systems can be increased by initiatives that support women-led cooperatives, providing targeted training and offering financial incentives (Chavarro Rodríguez & Moreno 2025). To ensure that postharvest technologies meet women farmers' requirements and socio-economic reality, rural sociologists and extension agents must collaborate closely with them.

Furthermore, the agricultural infrastructure still needs improvement, especially in rural areas where inadequate storage facilities, shoddy road networks, and unstable electrical supplies hamper postharvest efficiency. According to studies, perishable items frequently spoil before they are purchased, which results in financial losses and lower farmer incomes (Ogbu et al., 2021). Reducing postharvest losses and improving market access require investments in solar-powered preservation units, rural cold storage facilities, and upgraded transportation networks (Musa et al., 2023). Government regulations could also encourage the creation of aggregation systems, enabling farmers to combine their resources and make joint investments in processing and storage solutions (Ezeh et al., 2022). The key to the transmission of innovation is agricultural extension services, yet postharvest technological adoption is constrained by inadequate extension infrastructure. Many farmers lack access to training programs, technical support, and market information, reducing their ability to adopt modern storage and processing techniques (Becerra-Encinales, et. al., 2024). Promoting interdisciplinary training for extension agents ensures that farmers receive comprehensive support, bridging the gap between technical expertise and practical application (Okeke et al., 2021). Participatory extension models, farmer field schools, and ICT-driven advisory platforms are improving knowledge sharing and technology adoption. Additionally, biosystems engineers and extension professionals must co-create curricula for postharvest training, ensuring that farmers receive practical, hands-on education (Suleiman et al., 2021).

Therefore, to overcome these challenges, Nigeria must adopt a holistic approach that integrates policy, infrastructure, gender inclusivity, and extension services. Strengthening Public-Private Partnerships will foster collaboration between government agencies, research institutions, and agribusinesses to scale postharvest innovations (Nigeria Climate Innovation Centre, 2024). Similarly, Promoting Gender Inclusive Innovation Strategies: Implement women-led cooperatives, financial incentives, and targeted training programs to enhance women's participation in postharvest systems (JOPAFL, 2023). Furthermore, investing in Rural Infrastructure by developing cold storage facilities, solar-powered preservation units, and improved transportation networks will reduce postharvest losses and enhance market access (AgroNigeria, 2024).

Also, Enhancing Agricultural Extension Services will strengthen farmer training programs, participatory extension models, and ICT-driven advisory platforms to improve knowledge sharing and technology adoption (AJOL, 2023), and Designing Participatory Technology Development Processes will ensure that postharvest innovations align with local needs, incorporating user feedback into technology refinement (Balogun et al., 2021).

Conclusion

This review affirms that the postharvest sector of Nigeria operates within a complex ecosystem where innovation does not exist in isolation, but emerges through interactive networks of institutions, communities, and technologies. The Innovation Systems Approach captures this complexity by emphasising knowledge exchange, peer influence, trust networks, and responsive institutional frameworks. It reveals that successful technology adoption relies not only on invention but also on adaptation, accessibility, and sustained engagement among actors at every level.

Despite the development of impactful postharvest technologies by institutions such as the Nigerian Stored Products Research Institute, widespread adoption remains hindered by structural and socio-economic constraints. Weak policy enforcement, infrastructural gaps, gender disparities, and ineffective extension services have led to significant postharvest losses and persistent food insecurity. These challenges underscore the need for a coordinated, inclusive, and interdisciplinary approach.

To shift postharvest innovations from concept to transformation, Nigeria must commit to strengthening regulatory systems, investing in rural infrastructure, supporting gender-inclusive programming, and revitalising extension services. By fostering public-private partnerships and prioritising locally-driven innovation, stakeholders can ensure that technologies

align with user needs and contribute meaningfully to national development goals.

Recommendation

In light of the challenges and dynamics highlighted throughout this review, Nigeria must adopt a systems-driven and inclusive approach to strengthen its postharvest sector. Efforts should be concentrated on reinforcing public-private partnerships that bridge the divide between research institutions, agribusinesses, and government agencies. This will facilitate the development and scale-up of locally adapted postharvest technologies. Gender-inclusive strategies must be prioritised to empower women in processing, preservation, and extension roles, ensuring equal access to financial services, training programs, and mechanised tools. Investments in rural infrastructure such as solar-powered preservation units, improved transportation networks, and cold storage systems are essential to reduce spoilage and improve market access.

Additionally, reforming and expanding extension services through interdisciplinary training and ICT-based platforms will foster knowledge sharing and technology adoption. Finally, the institutional landscape must be aligned through coherent policy enforcement, participatory innovation frameworks, and sustained monitoring mechanisms. These strategies, implemented collectively, can reposition postharvest systems as a driver of food security, economic growth, and inclusive rural development.

Funding

This study is a desk-based qualitative review conducted independently, without financial support or influence from external organisations.

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